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DESIGN POINT STUDY OF AUXILIARY AIRBREATHING ENGINES FOR A SPACE SHUTTLE

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ABSTRACT

An analytical study was conducted of auxiliary airbreathing engines for a rocket-powered space shuttle. The purpose was to find the theoretical optimum engines. Only turbofans were considered for the booster because of long cruise times. Turbojets and turbofans were considered for the orbiter. The figure of merit was fuel and engine weight per pound of net thrust.

Turbofans were about 35 percent better than turbojets for the orbiter. For both stages, hydrogen was about 45 percent better than kerosene. To demonstrate the effect of improvements in engine technology, engine weight was decreased by one-half. This lowered the figure of merit about 20 percent. However, increasing turbine-inlet temperature showed little improvement.

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SUMMARY

An analytical engine performance study was conducted to determine the best auxiliary airbreathing engines for a rocket powered space shuttle. These engines are used to allow the two stages to reach a landing site and land. Turbofans were examined for the booster stage but both turbojets and turbofans were considered for the orbiter. Kerosene and liquid hydrogen fuels were compared and the effects of engine weight and design-turbine-inlet temperatures were studied. The turbine-inlet temperatures examined varied from 2100 to 2500° F (1148 to 1370° C) for kerosene and from 2500 to 3500° F (1370 to 1925° C) for hydrogen. Engine weight and cooling air bleed were not a function of design-turbine-inlet temperature. Installation penalties, take-off performance, ferry range, and non-standard days were not considered. The figure of merit was fuel and engine weight, per pound of net cruise thrust. Cruise times up to 2.0 hours for the boosters and up to 30 minutes for the orbiter were considered.

Results of the study show that the use of hydrogen fuel instead of kerosene will improve the figure of merit about 45 percent. Another way to improve the figure of merit is to reduce engine weight. A 50 percent reduction in engine weight gives an improvement of 20 to 25 percent. If a lighter engine means shorter engine life, it still may be acceptable since the running time per mission is not very long and few missions per year are planned.

Only small improvements were realized by increasing the design turbine-inlet temperature. Since the high temperature engines have greater thrust per pound of airflow, engine size is reduced and integration with the rocket vehicle will be facilitated. This effect was not analyzed in this study.

Turbofans demonstrated a 35 percent improvement over turbojets for the orbiter stage. However, only full power operation was considered. If part power cruise performance were considered some change in this comparison could result.

INTRODUCTION

There is currently a strong interest in a re-usable orbital booster or "space shuttle." Such a vehicle would have many uses. For instance, it could be used to launch satellites or to shuttle men and supplies to and from a space station. Interest in this concept is stimulated by a possible reduction in cost. If the same vehicle can be reused many times, instead of discarded as is done now, the cost of operation can be reduced.

For this study the space shuttle was considered to be a two-stage rocket-powered vehicle which was launched vertically. After separation of the orbiter stage, the booster stage will descend and decelerate to a good cruise altitude and Mach number. It will then use its auxiliary airbreathing engines to cruise to a landing field, such as the launch site, several hundred miles away and perform a conventional horizontal landing. The second stage continues into orbit under its own rocket power. After delivering its payload in space, it returns to Earth and lands at some preselected airfield in a conventional manner. Some small amount of cruise may be required before landing depending on the accuracy of the reentry. The airbreathing engines may be used for go-around or ferry missions also.

It is the purpose of this report to analytically investigate airbreathing engine cycle parameters. The analysis considers engine type, fuel type, design-turbine-inlet temperature, and other cycle variables. Optimum values are defined and sensitivity to departures from the optimum are investigated.

A cruise design point optimization was carried out to minimize fuel plus engine weight, per pound of cruise thrust, for varying lengths of cruise time. By normalizing the results with respect to thrust, the analysis is applicable to any of the many shuttle designs. For the purpose of centering the engine weight calculations around some reasonable size, a typical flight condition and level of cruise thrust was picked for the booster and the orbiter. The thrust level (per engine) picked was 25 000 pounds (11 300 kg) at 20 000 feet (6100 m) and Mach 0.4 for the booster and 20 000 pounds (9160 kg) at sea-level and Mach 0.3 for the orbiter. Based on these thrust levels, engine design airflow was calculated. This gave an indication of the relative physical size of the engines. No attempt was made to evaluate the actual physical size of the engines or the installation effects.

All the engines were optimized for kerosene and for liquid hydrogen fuel. Three turbine-inlet temperatures were examined for each fuel. They were 2100, 2300, and 2500° F (1148, 1260, and 1370° C) for JP and 2500, 3000, and 3500° F (1370, 1648, and 1925° C) for hydrogen fuel. No weight or cooling bleed air penalties were assumed as design turbine-inlet temperatures increased. This optimistic assumption was made in order to define the maximum possible benefits achievable with high temperature engines. All the engine weights were based on design parameters and calculated at two levels of technology.

Only turbofans were considered for the booster because of the long cruise time. The cycle parameters optimized were bypass ratio, overall compressor pressure ratio, and fan pressure ratio. In addition to the comparisons between fuel type, turbine-inlet temperature, and engine weight, several partially optimized turbofans with fixed bypass ratios were compared to the optimum engines. This demonstrated the sensitivity of the figure of merit to non-optimum engine cycle parameters.

Both turbofans and turbojets were considered for the orbiter. The engine parameters optimized for the turbofan were the same as mentioned for the booster. Only compressor pressure ratio was optimized for the turbojets. The optimum turbofan engines using hydrogen fuel were compared to the optimum turbojet engines and to three other turbofan engines which all shared the same gas generator.

METHOD OF ANALYSIS

The best altitude and Mach number for the subsonic cruise of the booster cannot be determined precisely for a general study. So the altitude and Mach number were chosen to be 20 000 feet (6100 m) and 0.4, respectively. The orbiter stage of the shuttle will use airbreathing engines during or just shortly prior to landing. For this reason the altitude was chosen as sea-level and the Mach number as 0.3.

The two fuels examined were kerosene (JP) and liquid hydrogen (H_2). JP is the most common jet fuel in use today but H_2 is the primary rocket fuel for the shuttle. So, both fuels have advantages. The only difference that will show up in this study is fuel weight which is related to the differences in heating value. No storage, volume, or fuel system weight changes were considered.

Choice of Engine Type

Booster. - Since the booster must fly hundreds of miles at subsonic speed to reach its landing site after orbiter separation, specific fuel consumption (SFC) is very important. Logically then, the turbofan engine was chosen to be studied for the booster. Engine weight is also important, but for a trip of a few hundred miles, it is of secondary importance compared to the fuel weight.

Orbiter. - The cruise time for the orbiter is even less defined than that of the booster. If a pin point re-entry is made, the engines may only idle as a safety factor. If the re-entry is not so accurate or if more flexibility is desired, the engines could operate for up to 30 minutes. But as the time for engine operation approaches zero, so does the fuel consumed. At some short time engine weight tends to be more important than fuel weight and hence SFC. For this reason the choice of engine type for the orbiter was not obvious and both turbojets and turbofans were studied.

Engine Weight Calculations

All the engine weights were based on an empirical method which correlates many existing engines. The method characterizes the engines in terms of total airflow, design turbine-inlet temperature, overall compressor pressure ratio, bypass ratio, and year of entry into service. The design cycle parameters at cruise are corrected back to sea-level-static conditions for the weight calculations. In this study the year was held constant at 1972 for consistency and the turbine-inlet temperature factor was held fixed in order to define the maximum benefits achievable with high temperature engines.

The engine weights calculated in this report are estimated to be 1972 cruise engine, or long life, technology and are referred to as a weight factor of 1.0. An example calculation to demonstrate how the method agrees with a real engine shows that a hypothetical engine having the same cycle characteristics as a TF-39 and coming into service in 1972 would weigh 6015 pounds (2730 kg). If this hypothetical engine came into service in 1968 as the TF-39 actually did, it was calculated to weigh 7736 pounds (3500 kg). The TF-39 actually weighs 7286 pounds (3300 kg).

The calculated weights were sometimes reduced by 50 percent and referred to as an engine with a weight factor of 0.5. This could be considered to correspond to a 1972 cruise type engine that has been lightened by 50 percent, with probably shortened

life, or to a new cruise engine of advanced technology that is still further in the future. Whatever it may be, it was used in this report strictly as a means of showing the effect of engine weight on performance.

Performance Calculations

While the net thrust required cannot be defined precisely at this time, a value was picked that seemed reasonable based on reference 1. This was done so that engine airflow, which is necessary for engine weight calculations, could be calculated. The net thrust per engine used in this study was 25 000 pounds (11 300 kg) for the booster at its cruise condition and 20 000 pounds (9160 kg) for the orbiter at its cruise condition.

Turbofan. - Engine performance was calculated for full-power design point operation at the cruise conditions. Two-spool engines were assumed. Both turbine efficiencies were fixed at 0.9 and the fan and compressor efficiencies were held at 0.88 and 0.86, respectively. Part-power performance was not considered in this study. Cooling air bleed was assumed to be 0.0 for all the engines so that the high-temperature engines would not be penalized.

After calculating the thrust per pound of air $(FN/\dot{W}_a)_{CR}$ at cruise the actual cruise airflow $(\dot{W}_a)_{CR}$ was determined since the required thrust $(FN)_{CR}$ had been assumed. Translating the design parameters to sea-level-static conditions allowed the engine weight (W_E) to be calculated by the method discussed. For any given flight time in hours, the weight of cruise fuel per pound of cruise thrust $(W_F/FN)_{CR}$ was determined by multiplying the specific fuel consumption (SFC) by time.

$$(W_F/FN)_{CR} = \text{SFC} \times \text{Time}$$

Adding to this the weight of engine per pound of cruise thrust (W_E/FN_{CR}) gives the figure of merit that was minimized in this study.

$$\text{Figure of merit} = \frac{W_E + W_{F_{CR}}}{FN_{CR}}$$

Given time, fuel type, weight factor, and turbine-inlet temperature, the figure of merit was minimized by varying the overall compressor pressure ratio, fan pressure ratio, and bypass ratio individually and repeatedly.

Turbojet. - The turbojet was studied in the same way as the turbofan. However, only the compressor pressure ratio was

optimized. The efficiencies of the compressor and turbine were fixed at 0.86 and 0.90, respectively. The figure of merit used in this report is useful since it is nearly independent of the actual level of thrust. The thrust requirements are vague because of the many vehicle configurations being considered at this time.

RESULTS AND DISCUSSION

The first section of the Results and Discussion concerns the booster stage of the shuttle. The effect of design-turbine-inlet temperature (T4), engine weight, and fuel type on the figure of merit are examined for dry turbofan engines. The second section concerns the orbiter stage of the shuttle. Both dry turbojets and dry turbofans are considered in this section. The engines studied in this report were always completely optimized at each time unless noted differently.

Booster

All the booster performance calculations were made at 20 000 feet (6100 m) and Mach 0.4 using dry turbofan engines only.

Turbofan using JP fuel. - Figure 1 shows the figure of merit (engine plus fuel weight, per pound of design thrust) plotted versus cruise time in hours. At a weight factor of 1.0, the figure of merit varies from 0.88 to 1.33 as time increases from 1.0 to 2.0 hours at a T4 of 2100° F (1148° C). When T4 is increased to 2500° F (1370° C) the figure of merit improves by 9.1 percent at 1.0 hours and 6.1 percent at 2.0 hours. This improvement is small, but it is the most to be expected because of the optimistic assumptions of no increase in engine weight or cooling air bleed for higher temperature engines.

The improvements from increasing T4 by 400° F (222° C) are rather small again for the weight factor 0.5 engines. This is evident from looking at the lower set of curves in this figure. However, if T4 is held at 2500° F (1370° C) and the engine weight is reduced by 50 percent, the figure of merit is improved by 22.6 percent at 1.0 hours and 18.4 percent at 2.0 hours. This is more than twice the improvement obtained by increasing T4 by 400° F (222° C). Although fuel consumption of a given engine varies linearly with time, none of the curves in figure 1 are straight lines. This is because the engine design parameters are constantly changing with time.

Figure 2 shows the engine parameters for the optimum engines at a weight factor of 1.0 and a T4 of 2500° F (1370° C). Also

shown is a curve for a bypass ratio 4 engine which will be discussed later.

At 1.0 hours the optimum bypass ratio is 8.0 and at 2.0 hours it is 15.0. Overall compressor pressure ratio varies between 23.0 and 30.0 and fan pressure ratios vary between 1.5 and 3.0 over the same time span. SFC is forced down from 0.48 to 0.425 hr^{-1} as the cruise time increases from 1.0 to 2.0 hours. This is because the fuel weight is becoming more important at the longer cruise times. The sea-level-static airflow necessary to achieve 25 000 pounds (11 300 kg) net thrust at 20 000 feet (6100 m) increases from 1800 to 2850 lb/sec (820 to 1290 kg/sec) as the time increases from 1.0 to 2.0 hours. These very large airflows result in large diameter engines which in turn could encounter problems in areas such as external drag and installation.

The thrust-to-weight ratio is shown for reference. However, it is the thrust at cruise conditions not sea-level-static thrust that is in the numerator of the thrust-to-weight ratio. It is preferable to show the thrust-to-weight ratio in terms of seal-level-static conditions but the accuracy of correcting cruise thrust to sea-level-static thrust without an analysis of off design performance was considered inadequate. The thrust-to-weight ratio shown decreases from about 3.1 to 2.5 for the optimum engines as time increases from 1.0 to 2.0 hours. The large optimum bypass ratio at 2.0 hours is the main cause for the decrease in thrust-to-weight ratio.

Figure 3 displays the effect of partial optimization at a weight factor of 1.0 and a T4 of 2500° F (1370° C). The bypass ratio was fixed at 2.0 and 4.0, and the other engine parameters were optimized. The curve for the bypass ratio of 4 shows that the figure of merit has been degraded only 3.0 percent at 1.0 hours and 10.4 percent at 2.0 hours compared to the optimum engines. The bypass ratio 2.0 engine is a little worse. These fixed bypass ratio engines were considered in order to compare their design parameters to those of the optimum engines.

Returning to figure 2, the curves labeled bypass ratio 4 demonstrate no significant changes in design parameters when compared to the optimum engines, except that the fan pressure ratio is higher and the airflow lower. The airflow is about 1240 lb/sec (562 kg/sec) at cruise times from 1.0 to 2.0 hours. This is a reduction of 33 percent at 1.0 hours and 56 percent at 2.0 hours from the optimum engine level. So the bypass ratio 4 engines should present fewer problems with respect to installation and drag than the optimum engines if the higher fan pressure ratio does not cause a problem. It is clear, however, that engine design parameters can depart significantly from the optimum without much penalty in the figure of merit.

Turbofan using H_2 fuel. - Figure 4 shows the results of optimizing turbofan engines at a weight factor of 1.0 using H_2 fuel. Three T4 temperatures are shown, each 500° F (278° C) apart. The lower three curves are for the completely optimized engines at the temperatures noted. The two dashed curves are for engines that have been optimized at the fixed bypass ratios noted. A single weight factor of 1.0 is used because the effect of engine weight is essentially the same as it was for the JP turbofans. At a T4 of 2500° F (1370° C), the figure of merit varies from 0.45 at 1.0 hours to 0.66 at 2.0 hours. Increasing T4 to 3500° F (1925° C) improves the figure of merit by 11 percent at 1.0 hours and 10 percent at 2.0 hours. The improvement is small for so large a change in T4 especially since the high temperature engines were not penalized in any way.

Fixing the bypass ratio at 4 and re-optimizing the other parameters at a T4 of 2500° F (1370° C) degrades the figure of merit by 2.2 percent at 1.0 hours and 3.1 percent at 2.0 hours compared to the optimum engines at the same T4. The partially optimized engines at a fixed bypass ratio of 2.0 are slightly worse than those at a bypass ratio of 4.0.

Figure 5 compares optimum design parameters for engines having unrestricted bypass ratios and those where the ratio is fixed at 4.0. Because the heating value of H_2 is higher than for JP, good SFC can be achieved at lower bypass ratios with H_2 fuel than with JP fuel. As a result, the optimum bypass ratios are lower for the H_2 fueled engines and the other optimum engine parameters are close to the optimum engine parameters for the bypass ratio 4 engines. However, the sea-level-static airflow of the two engines are dissimilar. The airflow required for the bypass ratio 4 engines is equal to that of the optimum engine at 1.0 hours, but at 2.0 hours it is 23 percent less than for the optimum engine. This was the main reason for considering the bypass ratio 4 engines. Note that the airflow reduction, when switching from the optimum engines to the bypass ratio 4 engine, is not nearly as large at 2.0 hours as it was for the JP turbofans considered in figure 2. However, even a 23 percent reduction in airflow should relieve some of the installation problems by reducing the engine diameter.

Summary of turbofans using JP and H_2 fuel. - Most of the conclusions drawn so far can be seen more clearly by examining figure 6. In figure 6, both weight factors and both fuel types are shown. The figure of merit is plotted versus T4 for a fixed cruise time of 1.0 hours.

It is obvious from the slope of the curves that the effect that T4 has on the figure of merit is indeed small. These small benefits should be viewed as the best that can be achieved

because no weight or cooling air bleed penalties were assessed at high turbine-inlet-temperatures. The actual improvement over the respective T4 ranges was 8.75 percent for JP and 11.0 percent for H_2 at a weight factor of 1.0. On the other hand, reducing engine weight by 50 percent improves the figure of merit by 23.5 percent for JP and 26.7 percent for H_2 at 2500° F (1370° C). If lighter engines mean shorter life for the engines, this may be acceptable since the booster will probably make no more than 25 trips per year.

Using H_2 fuel instead of JP yields the largest improvement in figure of merit of any of the methods studied. At 2500° F (1370° C) H_2 improves the figure of merit by 46.5 percent and by 47.0 percent for weight factors of 1.0 and 0.5, respectively.

The effect of changes in airbreathing engine system weight on the lift-off gross weight (WG_{LO}) of the entire shuttle can be appreciated with the aid of reference 1. Reference 1 indicated that WG_{LO} changes at the ratio of 5 to 1 for each incremental change in booster burnout weight. This assumes a fixed payload (orbiter weight) and velocity at the separation of booster and orbiter. For example, if the required thrust of the turbofan engines is assumed to be 100 000 pounds (45 359 kg) total for four engines, then a switch from JP to H_2 saves 36 000 pounds (16 300 kg) in engine and fuel weight for a T4 of 2500° F (1370° C) and a weight factor of 1.0. This corresponds to a reduction in WG_{LO} of 180 000 pounds (81 500 kg) based on the 5 to 1 ratio.

ORBITER

All the engine performance calculated for the orbiter was at sea-level and Mach 0.3 where the net thrust required was 20 000 pounds (9160 kg). Turbojets and turbofans are discussed in this section of the report and in that order. The turbojets are optimized using JP and H_2 fuel but only H_2 fuel is used for the turbofans. At the end of this section the turbojets and turbofans are compared while using H_2. The cruise time span studied for the orbiter was essentially from 0.05 hours to 0.5 hours.

Turbojet using JP fuel. - In figure 7, the figure of merit is plotted versus cruise time for JP fueled turbojets at the temperatures noted. For a weight factor of 1.0, the figure of merit is better at 2500° F (1370° C) than at 2100° F (1148° C). However, as time increases the gains from the higher T4 decrease until at 0.25 hours there is no difference between the curves. Considering the curves for a weight factor of 0.5, it can be seen that higher T4 yields very little improvement at short times and actually degrades the figure of merit at times greater than 0.15

hours. The higher T4 does reduce the engine size and the engine weight per pound of thrust, but the SFC increase offsets this gain. No weight or cooling air bleed penalties have been assessed against the high-temperature engines.

Reducing engine weight by one-half improves the figure of merit by 32.3 percent at 0.05 hours and 17.0 percent at 0.25 hours for a T4 of 2500° F (1370° C). If these lighter engines mean shorter engine life than for normal cruise engines, this may be acceptable. Since orbiter cruise time is shorter than booster time, engine life may be somewhat less important.

The optimum dry turbojet engine parameters are shown in figure 8 for a JP fueled engine at a T4 of 2500° F (1370° C) and a weight factor of 1.0. The compressor pressure ratio increases from 11.5 at 0.05 hours to 17.5 at 0.25 hours. Over the same time span the SFC decreases from 1.18 to 1.06 and the sea-level static airflow needed to meet the assumed thrust requirements at cruise decreases from 216.5 to 209.0 lb/sec (98.3 to 94.8 kg/sec). The airflow required is small enough so that problems related to engine diameter are minimal. The cruise thrust-to-weight ratio varies from 10.2 to 8.6 as time increases from 0.05 to 0.25 hours.

Using H_2 fuel and re-optimizing the dry turbojet yields the results shown in figure 9. Note the range of T4. For a weight factor of 1.0, a T4 of 3500° F (1925° C) was best until a cruise time of 0.25 hours where the values of T4 studied no longer had an effect on the figure of merit.

At a weight factor of 0.5, a T4 of 3500° F (1925° C) is again best at short cruise times. But at times greater than 0.14 hours a T4 of 2500° F (1370° C) is actually better. This figure demonstrates again that a reduction in engine weight of 50 percent shows more improvement in the figure of merit than increasing T4 by 1000° F (555° C).

The optimum engine parameters for the H_2 fueled turbojet engines are plotted in figure 10 for a weight factor of 1.0 and a T4 of 2500° F (1370° C). Comparing them to the JP turbojets shows that the H_2 fueled turbojets achieve good SFC at lower compressor pressure ratios. The resulting sea-level-static airflows are similar but the cruise-thrust-to-weight ratios of the H_2 fueled turbojets are higher than those of the JP fueled turbojet. The values shown for the design parameters are reasonable and probably will not cause severe design or installation problems.

<u>Summary of turbojets using JP and H_2 fuel</u>. - Figure 11 summarizes the results of the dry turbojet study for a cruise time of 0.25 hours. Both fuel types are shown at both weight factors and the figure of merit is plotted versus T4.

Changing T4 within the ranges shown yields no improvements in the figure of merit at a weight factor of 1.0 for either fuel. Increasing T4 within the limits shown actually causes a slight degradation in the figure of merit at a weight factor of 0.5 for both fuels. Again, engine weight and cooling air bleed were not a function of T4. The only benefit of higher T4 is a smaller engine airflow. For example, increasing T4 over the range shown for each fuel at a weight factor of 1.0, reduces the sea-level-static airflow from 254 to 210 lb/sec (115 to 95 kg/sec) for JP and from 203 to 148 lb/sec (92 to 67 kg) for H_2. Whether this much change in airflow is important is unclear at this time.

Changing the weight factor from 1.0 to 0.5 produces a marked improvement in the figure of merit. The improvements were 19.7 and 17.1 percent for JP at 2100° F and 2500° F (1148 and 1370° C), respectively and 23.8 and 19.0 percent for H_2 at 2500° F and 3500° F (1370 and 1925° C). Switching from JP to H_2 fuel at a weight factor of 1.0 and a T4 of 2500° F (1370° C) provided an improvement of 46 percent. Therefore, hydrogen can provide significant improvements over JP for turbojets if there are not any large weight penalties in the engine or fuel system.

A change in orbiter burnout weight can be translated into a change in WG_{LO} of the entire shuttle. For a fixed payload and staging velocity the ratio of change in WG_{LO} to change in orbiter burnout weight is shown to be about 20 to 1 in reference 1. Based on an estimated total orbiter cruise thrust of 80 000 pounds (36 250 kg) for four engines, switching from JP to H_2 will save 14 000 pounds (6350 kg) at a T4 of 2500° F (1370° C) and a weight factor of 1.0. At the ratio of 20 to 1, this savings in the orbiter auxiliary engine and fuel weight means that the WG_{LO} of the shuttle could be reduced by about 280 000 pounds (127 000 kg). If the shuttle weighed 4 000 000 pounds (1 810 000 kg), this would be a 7 percent weight reduction. Or looking at it another way, a 14 000 pound (6350 kg) savings in orbiter weight is the same as an equal payload increase if the payload volume and shuttle WG_{LO} are unchanged.

Turbofan using H_2 fuel. - Dry turbofans were also analyzed for the orbiter using H_2 fuel. In figure 12, the figure of merit for H_2 fueled turbofans at a weight factor of 1.0 and a T4 of 2500° F (1370° C) is plotted versus orbiter cruise time. The effect of T4, weight factor, and fuel type are not shown since all of these effects are essentially the same as shown for turbofans in the booster stage. The figure of merit for the optimum turbofan varies from 0.1 at 0.1 hours to 0.192 at 0.5 hours. The level is somewhat better than it was for the turbojet as will be discussed later.

There are three other curves on this figure labeled bypass ratio 2, 3, and 4. These engines have been optimized at the bypass ratios shown, but in contrast to the partially optimized booster engine calculations, the core pressure ratio was fixed at 9.0.

Only the fan pressure ratio and airflow were allowed to optimize at various times. At times of 0.25, 0.325, and 0.52 hours for the bypass ratios of 4, 3, and 2, respectively, the engines optimized so as to give a core corrected airflow of 50 lb/sec (22.6 kg/sec). Since the core pressure ratio and corrected airflow was constant at these three times, these engines all utilize the same core. Straight lines were drawn through the three points at the slope as determined from the SFC. These are the curves labeled bypass ratio of 2, 3, and 4. They are straight lines because the engines are not reoptimized with time as all the partially optimized engines were for the booster.

The preceding calculations were prompted by the fact that often manufacturers will build one core engine to be used with several fans for different purposes. The presented calculations demonstrate that if such a core were available, several specific fans could be driven by it which would give results almost as good as the truly optimum engines. The pressure ratio and corrected airflow of the core compressor were chosen because they were similar to those of several modern-day core engines.

The curves in figure 12 demonstrate that the bypass ratio 4 engine has been degraded only 5.0 percent at 0.25 hours compared to the optimum engine. The other fixed bypass ratio engines are slightly inferior to the bypass ratio 4 engine.

The parameters corresponding to the optimum engines and the bypass ratio 2, 3, and 4 engines are shown in figure 13. Any one of the engines looks satisfactory from the standpoint of design parameters. However, if sea-level-static airflow is of concern because of engine diameters, the lower bypass ratio engines require less airflow.

Summary of turbojets and turbofans using H_2 fuel. - Figure 14 summarizes the study made for the orbiter. The figure of merit is plotted versus design T4 for H_2 fueled turbojets and turbofans at both weight factors for a cruise time of 0.25 hours.

Changing T4 from 2500 to 3500° F (1370 to 1925° C) offsets the figure of merit very little at either weight factor and for either engine. Benefits of high-turbine-inlet temperatures are therefore negligible except for the reduction in engine airflow which it can achieve. Changing the weight factor from 1.0 to 0.5 helps the figure of merit significantly. The improvements are 23.8 percent at 2500° F (1370° C) and 19.0 percent at 3500° F (1925° C) for the turbojet. For the turbofan, the improvements are 25.8 percent and 23.3 percent at the same temperatures.

The improvement in the figure of merit when switching from a turbojet to a turbofan is 34.2 percent at 2500° F (1370° C) and a

weight factor of 1.0. This means a savings of 5600 pounds (2535 kg) in auxiliary engine and fuel weight for the orbiter if the net thrust for four engines is assumed to be 80 000 pounds (36 200 kg). Using the growth factor of 20 to 1 from reference 1, this weight savings means a savings of 112 000 pounds (50 700 kg) in WG_{LO} of the entire shuttle. If WG_{LO} was fixed, the 5600 pound (2535 kg) weight savings could be turned into an equal amount of payload increase providing the payload volume did not increase. Regardless of how it is viewed, the orbiter weight is very important and every possible means of lightening the orbiter should be investigated.

CONCLUDING REMARKS

Auxiliary airbreathing engines for a two-stage rocket-powered space shuttle were studied analytically. The shuttle was composed of a booster first stage and an orbiter second stage. The purpose of this study was to define the engine cycle characteristics that minimize the weight of engine plus fuel at any given length of cruise time. Only turbofan engines were examined for the booster, but turbojets and turbofans were examined for the orbiter stage.

The two fuel types used in the study were kerosene (JP) and liquid hydrogen (H_2). The design turbine-inlet-temperatures investigated ranged from 2100 to 2500° F (1148 to 1370° C) for JP and from 2500 to 3500° F (1370 to 1925° C) for H_2. Two weight technology levels were used. One level corresponded to 1972 cruise engines (i.e., a new engine going into service in 1972). The other technology level can be viewed as an advanced technology cruise engine going into service much later than 1972 or a 1972 cruise engine which has been lightened 50 percent with a somewhat shorter engine life. Cruise times were up to two hours for the booster and up to 30 minutes for the orbiter. Cruise altitude and Mach numbers were 20 000 feet (6100 m) and 0.4 for the booster and sea-level and 0.3 for the orbiter.

This was a preliminary study and as such did not consider non-standard days, take off and ferry requirements, engine-out requirements, and off design performance.

It was found that using H_2 fuel instead of JP gave about 45 percent improvement in the figure of merit for the booster at cruise times of 1.0 to 2.0 hours. The improvement was between 35 and 45 percent for the orbiter at times from 0.05 to 0.25 hours. No weight penalties were assumed for switching from JP to H_2 fuel.

Reducing the engine weight by 50 percent from the cruise engine level improved the figure of merit by about 20 to 25 percent. These lighter engines, presumably with short life, may be adequate

for the space shuttle application since the cruise times are short and few trips are planned per year.

Turbofan engines were found more attractive than turbojets for the orbiter stage application. When turbofans were used instead of turbojets, the figure of merit improved by about 35 percent. Turbofan engines then are very attractive for both stages in terms of fuel plus engine weight. However, many of the optimum turbofan engines required bypass ratios as high as 15. This could be of concern from several standpoints such as engine installation and drag penalties. Therefore, it is worth noting that considerable departure from the optimum designs, to accommodate these factors and/or to utilize an existing engine, can be tolerated without major weight increases.

Only small improvements were found when design-turbine-inlet temperatures were increased. Raising the temperature from 2100 to 2500° F (1148 to 1370° C) for JP fueled engines gave improvements no greater than 10 percent in the figure of merit. In some cases, the figure of merit actually decreased as the temperature was increased. When the temperature was increased from 2500 to 3500° F (1370 to 1925° C) for the H_2 fueled engines, there was usually an improvement in the figure of merit. But at best, the improvements were small compared to those obtained through using H_2 fuel or by reducing engine weight by 50 percent from the cruise engine level. Since no penalties in engine weight or cooling bleed were charged against the higher design-turbine-inlet temperature engines, it was concluded that increasing the design-turbine-inlet temperature beyond 2500° F (1370° C) was not an effective way to improve the figure of merit. However, it may be worth considering if engine design airflow needs to be decreased in order to reduce the size of the engine.

The optimized hypothetical engines represent goals against which to measure existing engines. They also indicate what direction modifications might take in order to make existing engines more suitable for the space shuttle. And finally, within the limitations of this report, they provide trends in design parameters that are desirable should a new engine be developed.

Lewis Research Center,
National Aeronautics and Space Administration
Cleveland, Ohio, April 30, 1970
126-15-13

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1. Anon.: Study of Integral Launch and Reentry Vehicle System. Vol. 4: Second Phase Design and Subsystems Analysis. Rep. SD-69-573-4, North American Rockwell Corp. (NASA CR-102105), Dec. 1969.

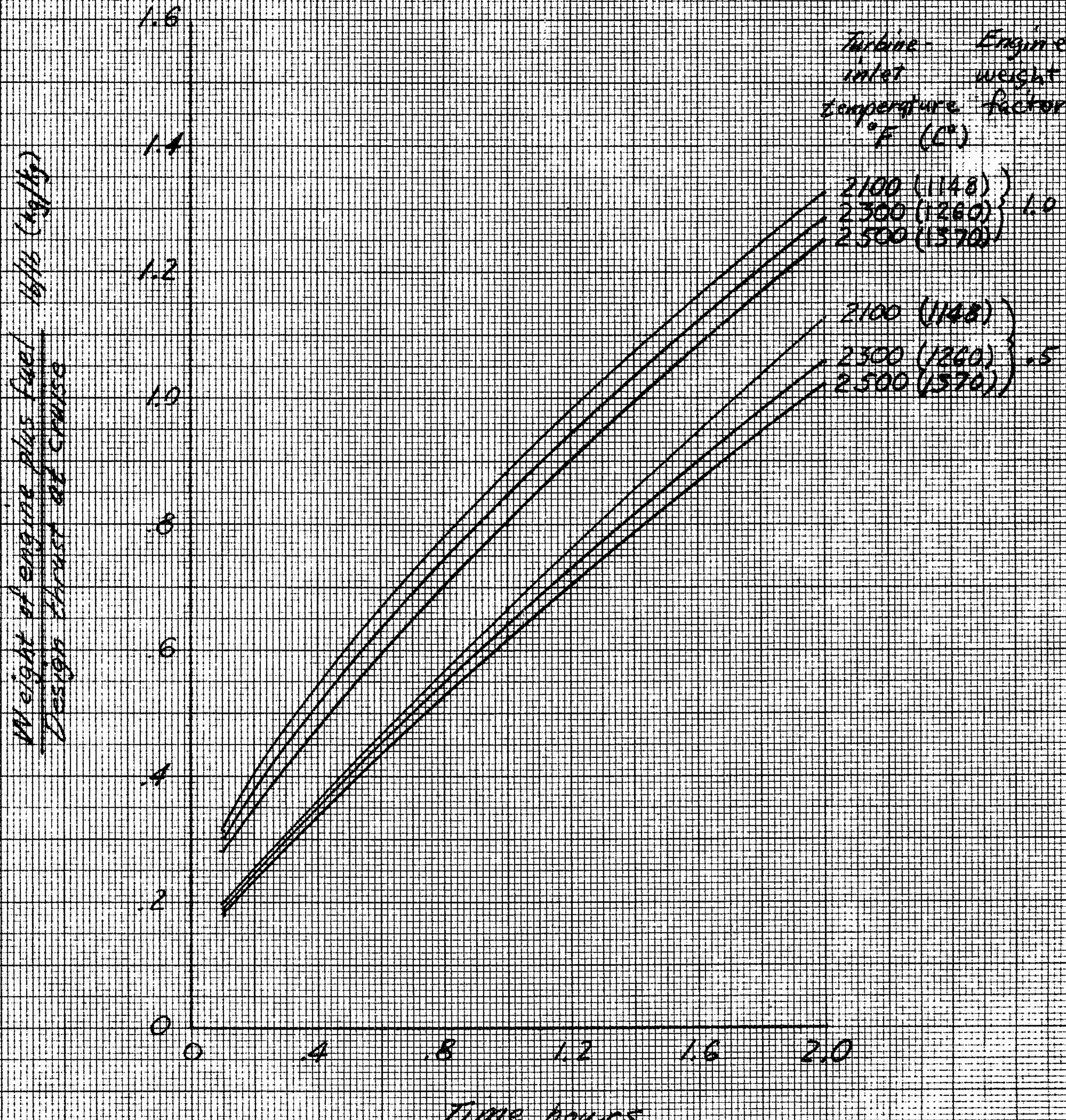

Figure 1.- Optimum dry turbofan engines scaled to produce 25000 lb (11300 kg) net thrust at MN=0.9, 20000 feet (6100 m) using JP fuel.

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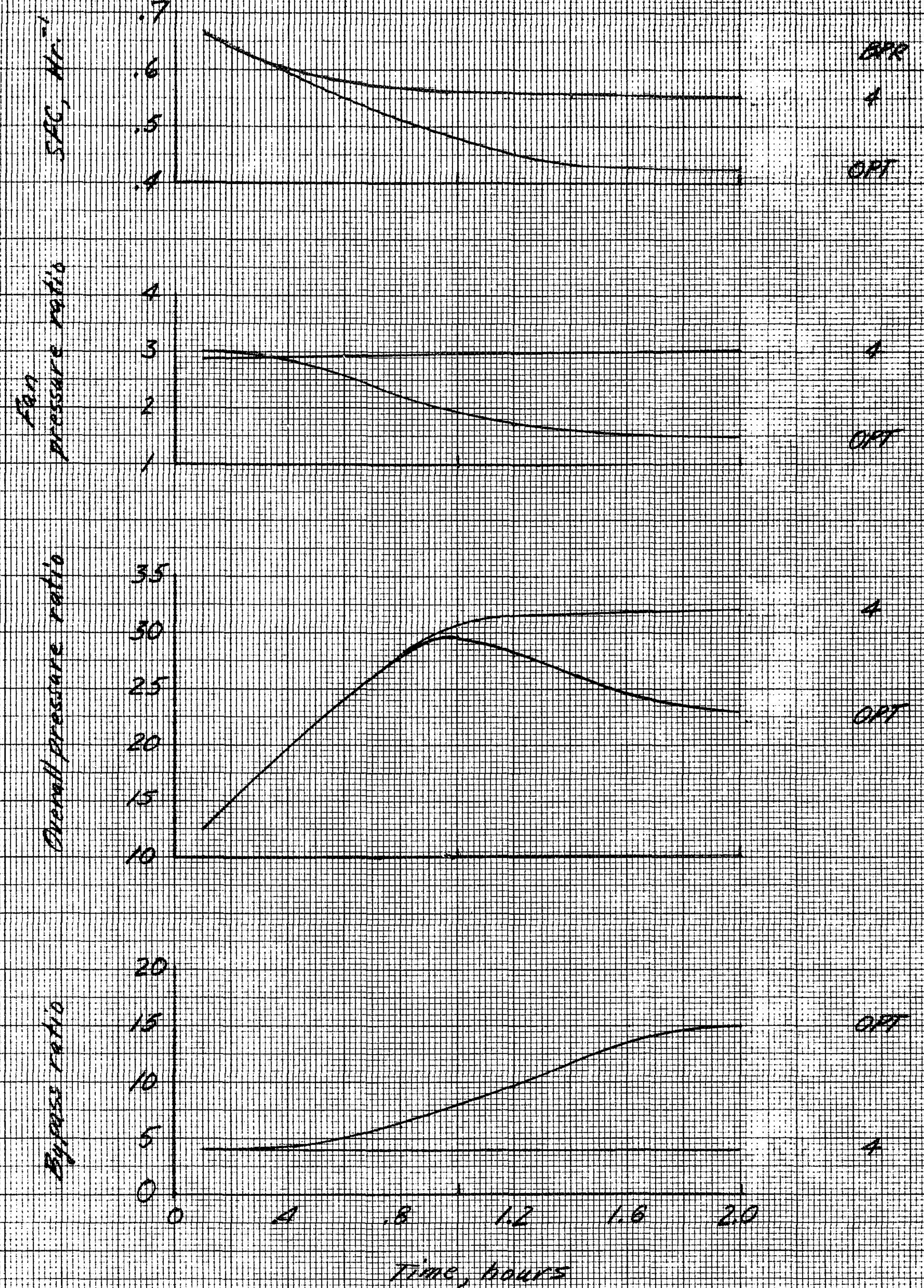

Figure 2.- Engine parameters for dry turbofan engines scaled to produce 25000 lb (11300 kg) net thrust at MN=0.4, 20000 feet (6100m) using JP fuel. Weight factor = 1.0. Turbine-inlet temperature = 2500°F (1370°C)

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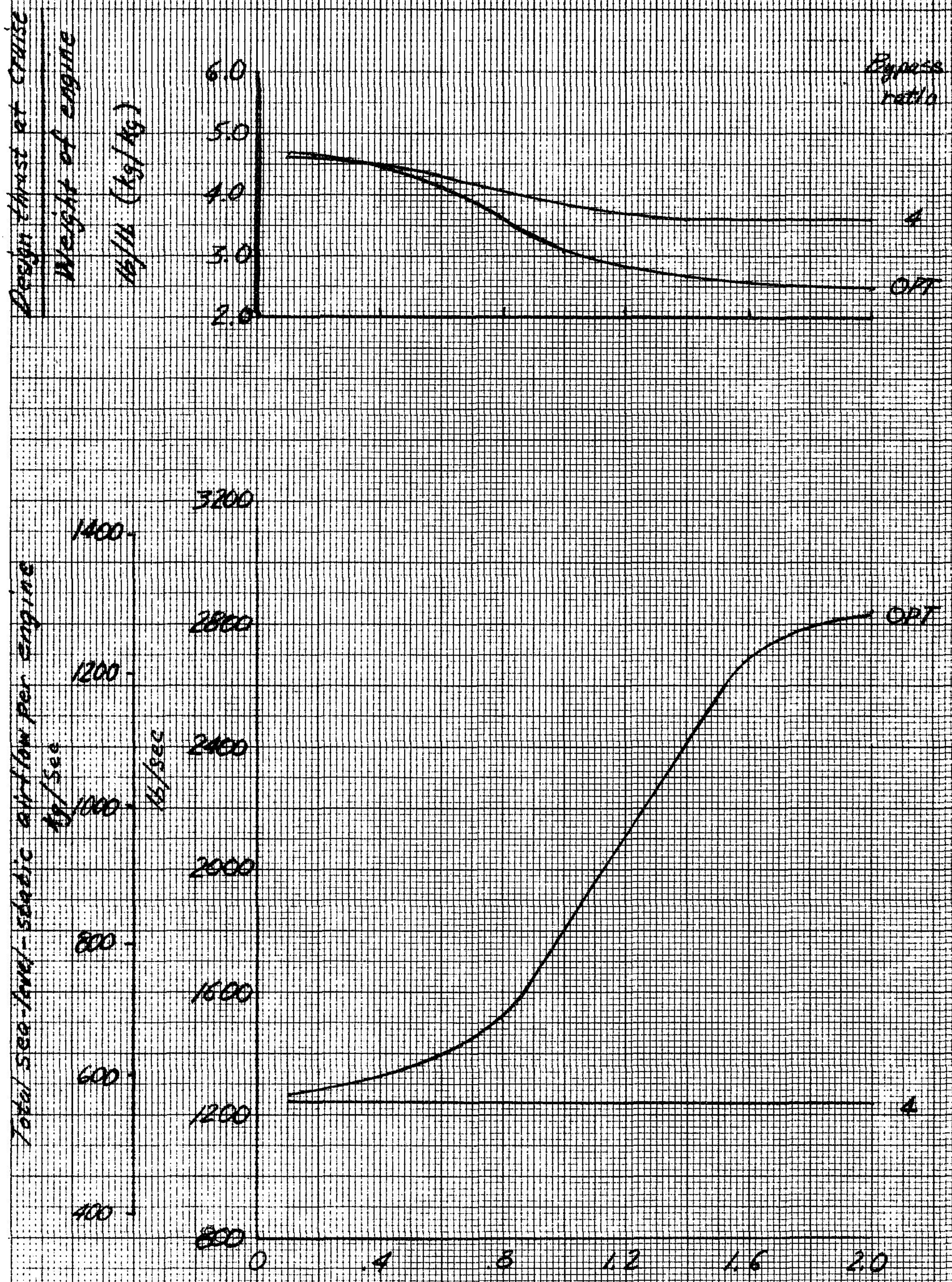

Figure 2.- (Cont.)

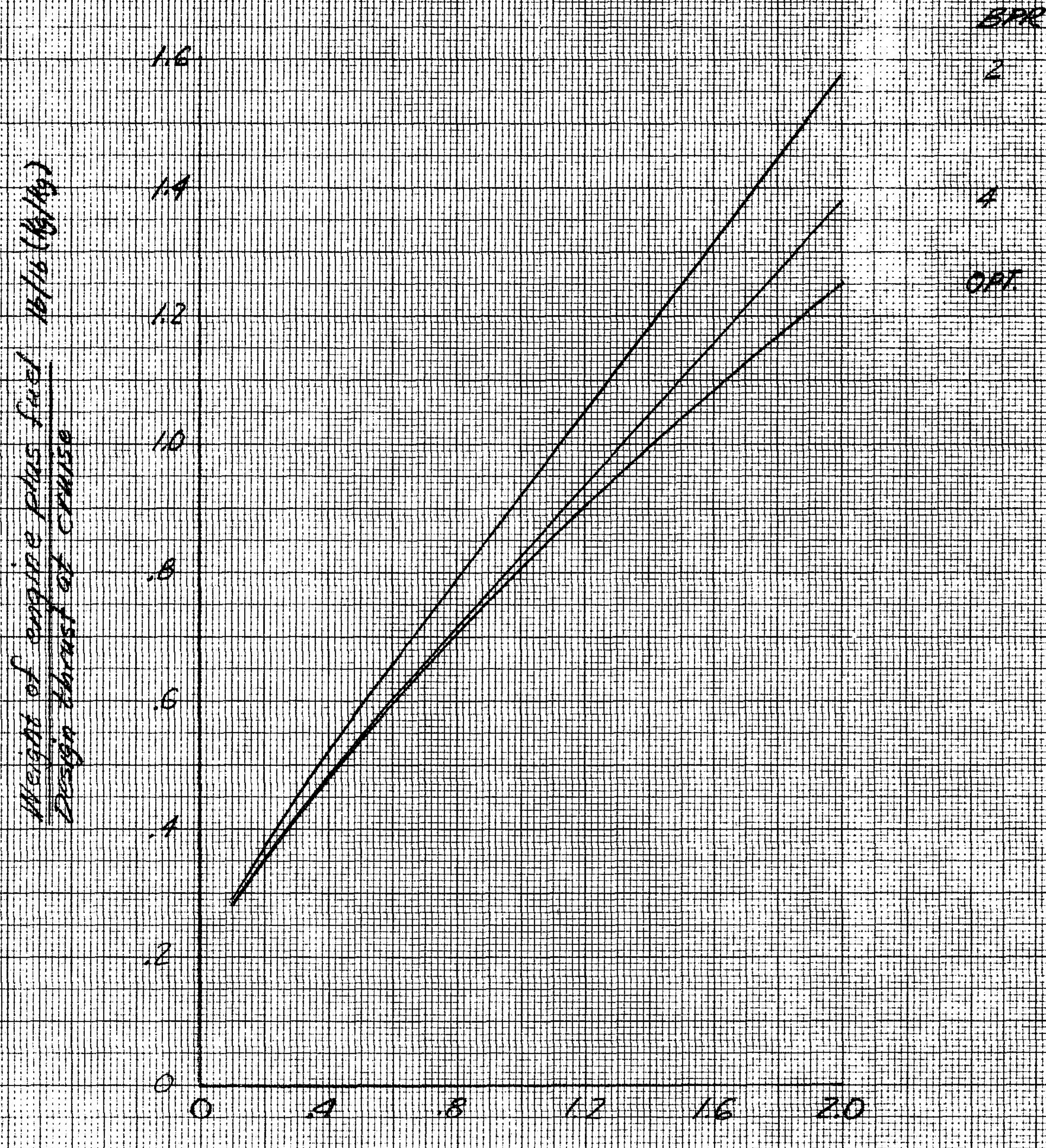

Figure 3.- Comparison of optimum and fixed bypass ratio dry turbofan engines scaled to produce 25000 lb (11300 kg) net thrust at MN = 0.4, 20000 feet (6100 m) using JP fuel. Weight factor = 1.0. Turbine inlet temperature = 2500 °F (1370 °C)

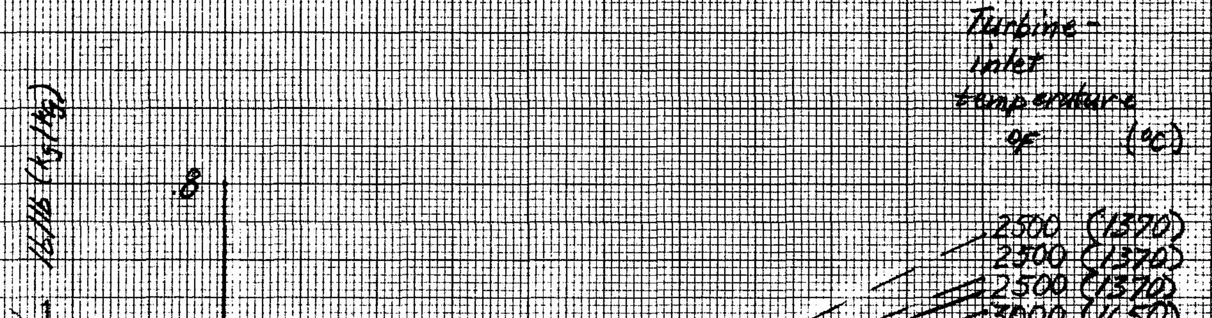

Figure 4.- Comparison of optimum and fixed bypass ratio dry turbofan engines scaled to produce 25000 lb (11300 kg) net thrust at MN=0.9, 20000 feet (6100 m) using H_2 fuel. Weight factor = 1.0.

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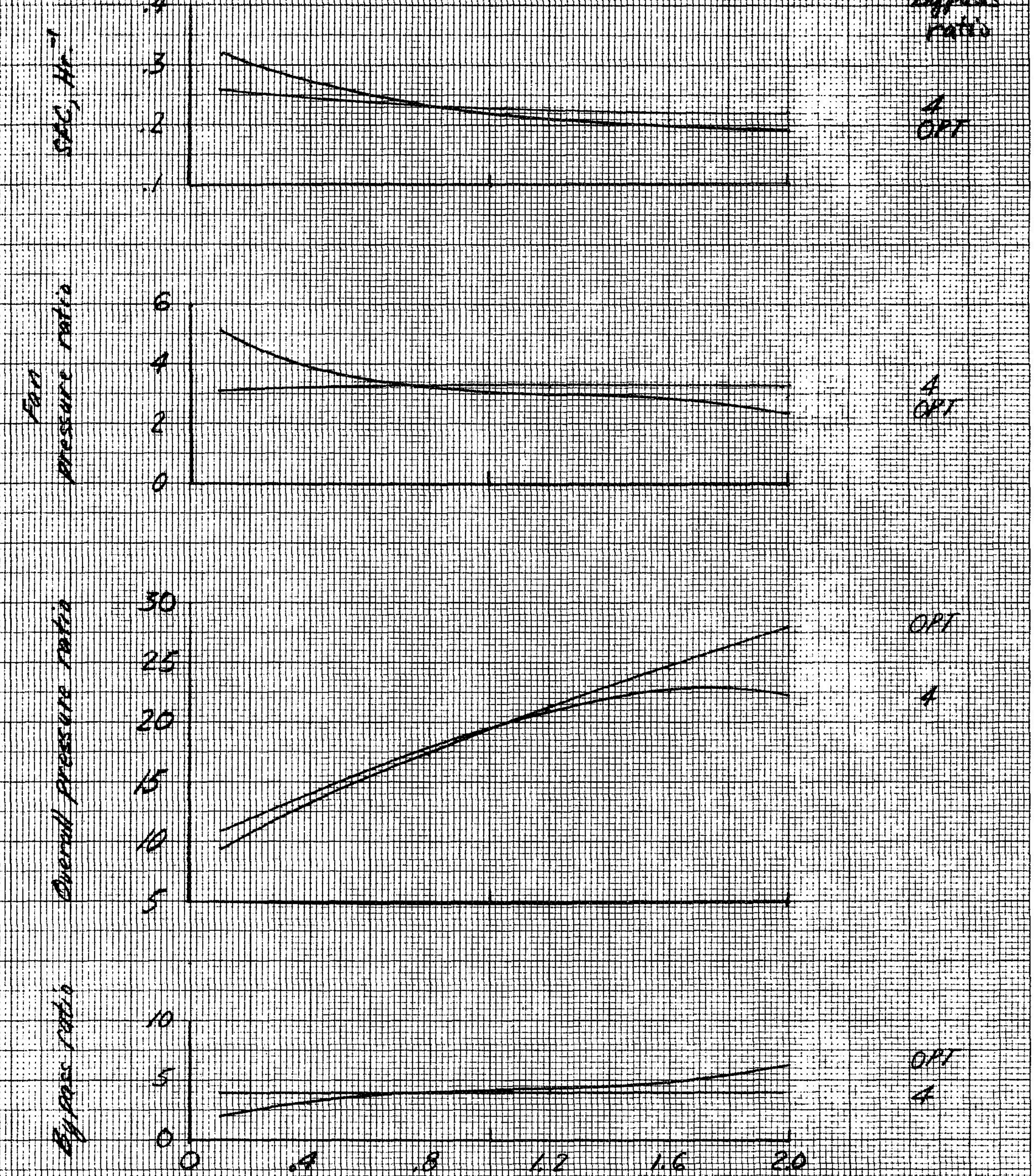

Figure 5.- Engine parameters for dry turbofan engines scaled to produce 2500 lb (1130 kg) net thrust at MN = 0.4, 20000 feet (6100 m) using H_2 fuel. Weight factor = 1.0. Turbine-inlet temperature = 2500°F (1370°C)

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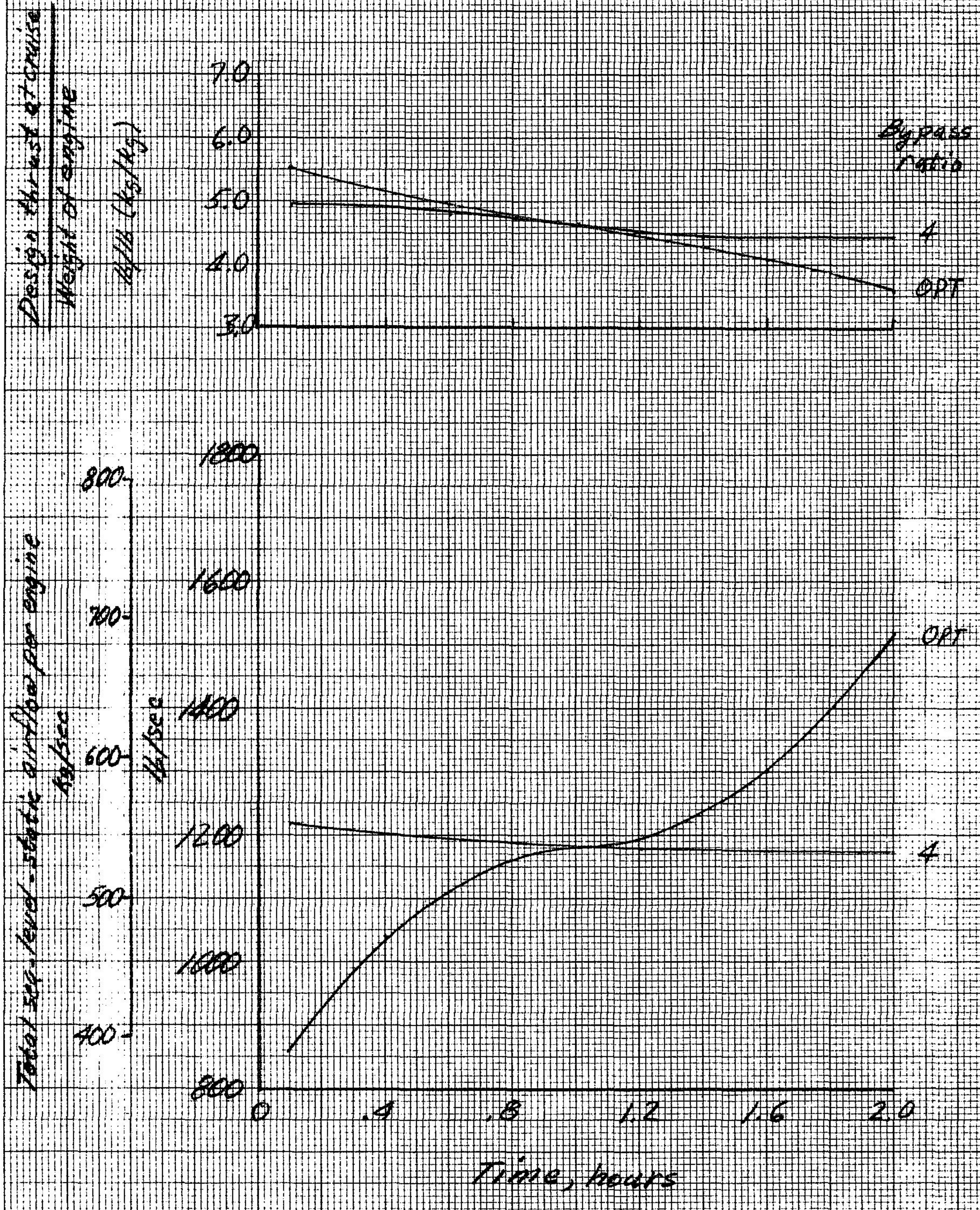

Figure 5.- (Cont.)

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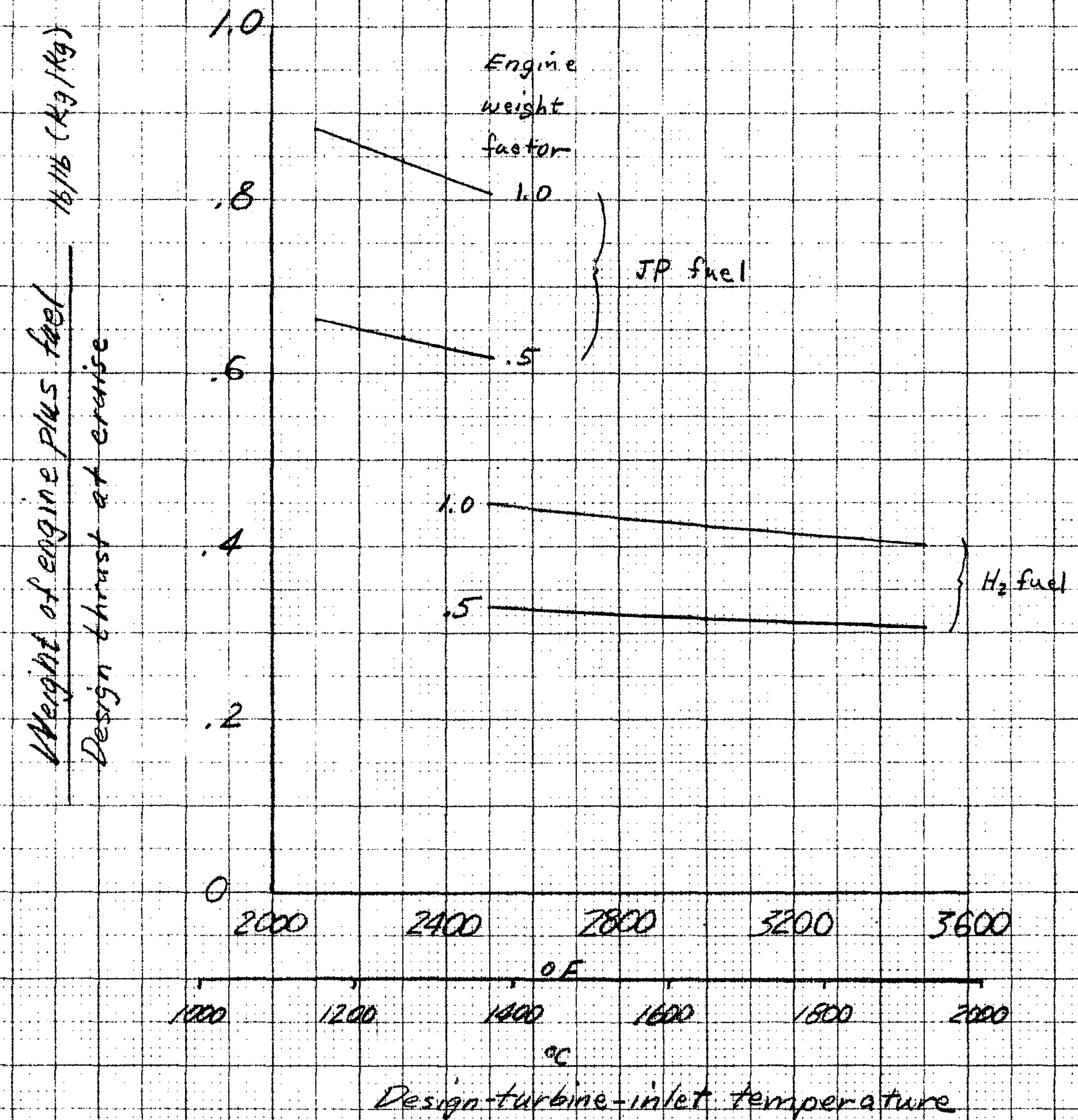

Figure 6. - Summary of optimized turbofan engines scaled to produce 25000 lb (11300 kg) net thrust at MN = 0.4, 20000 feet (6100 m). Cruise time = 1 hour.

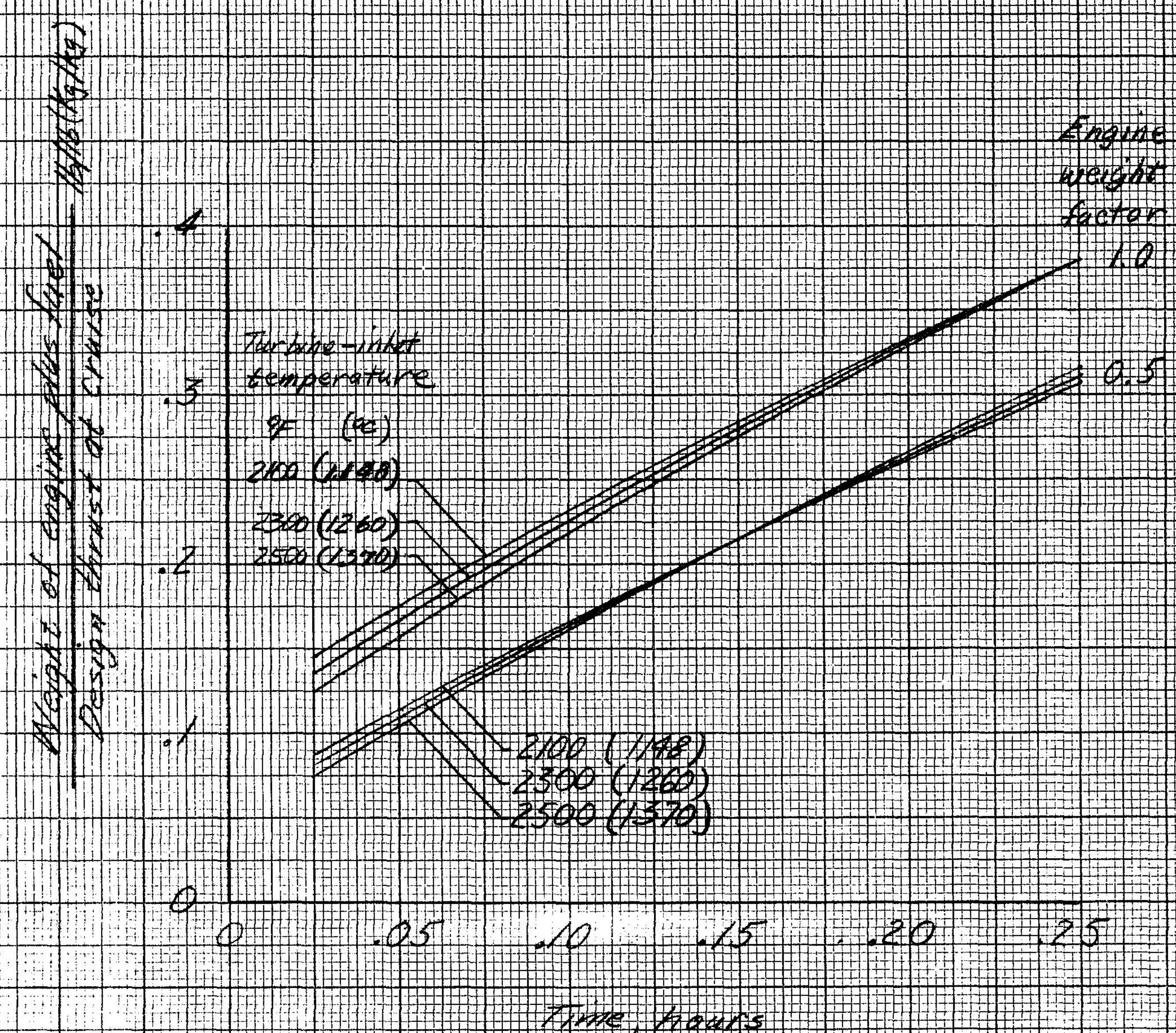

Figure 7. - Optimum dry turbojet engine scaled to produce 20000lb(9160kg) net thrust at MN = 0.3, sea-level using JP.

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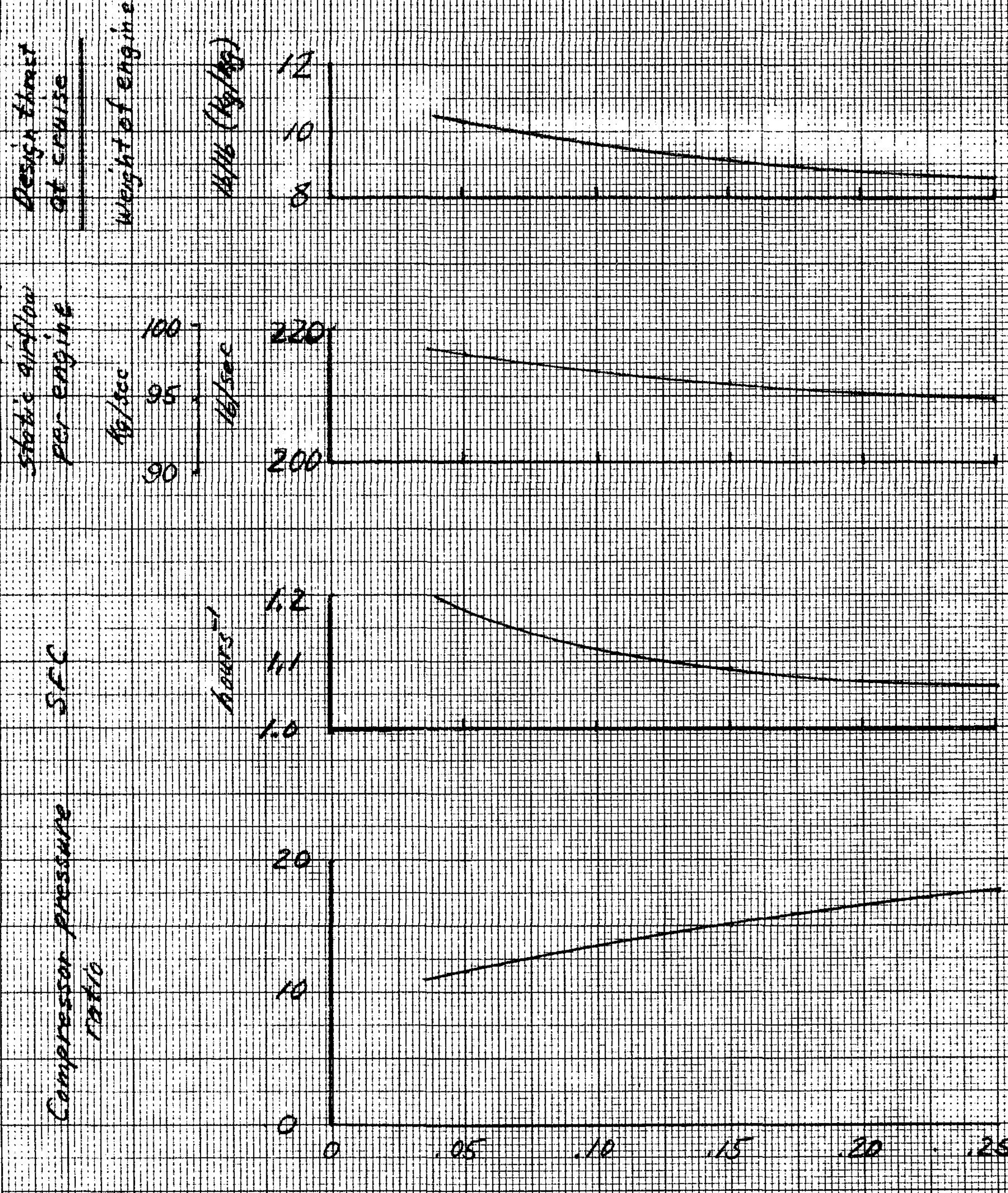

Figure 8.- Engine parameters for dry turbojets scaled to produce 20000 lb (9160 kg) net thrust at MN = 0.3, sea-level using JP. Weight factor = 1.0, turbine-inlet-temperature = 2500°F (1370°C)

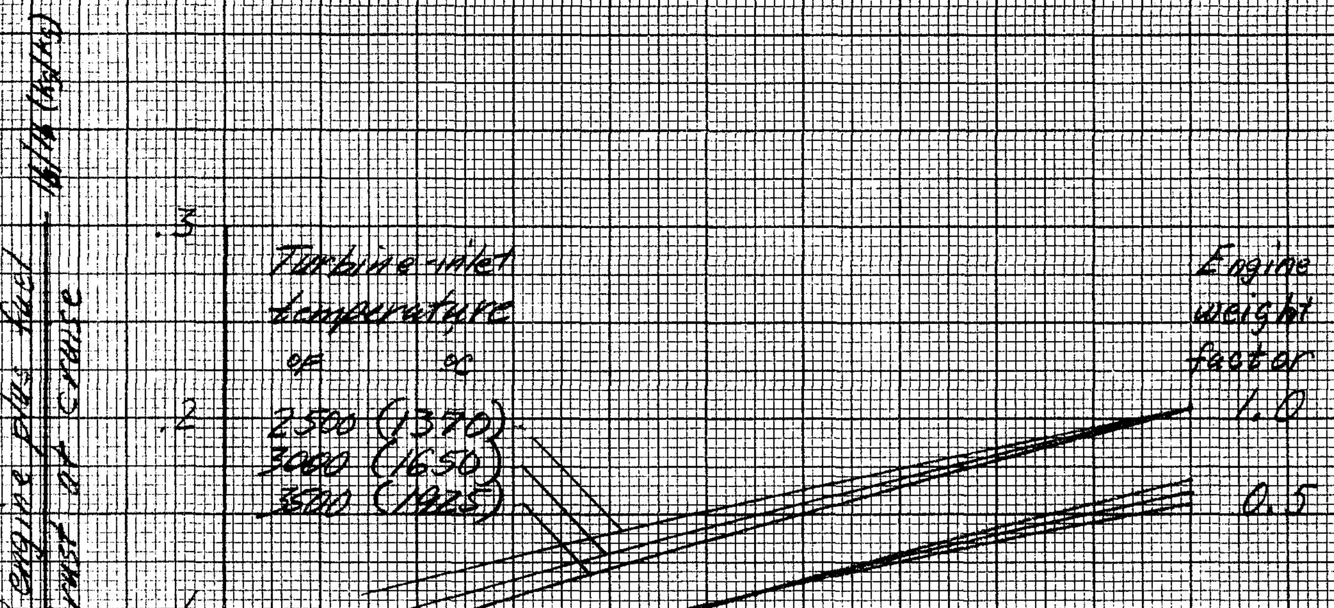

Figure 9.- Optimum dry turbojet engine scaled to produce 20000 lb (9160 kg) net thrust at M = 0.3, sea level using H_2 fuel.

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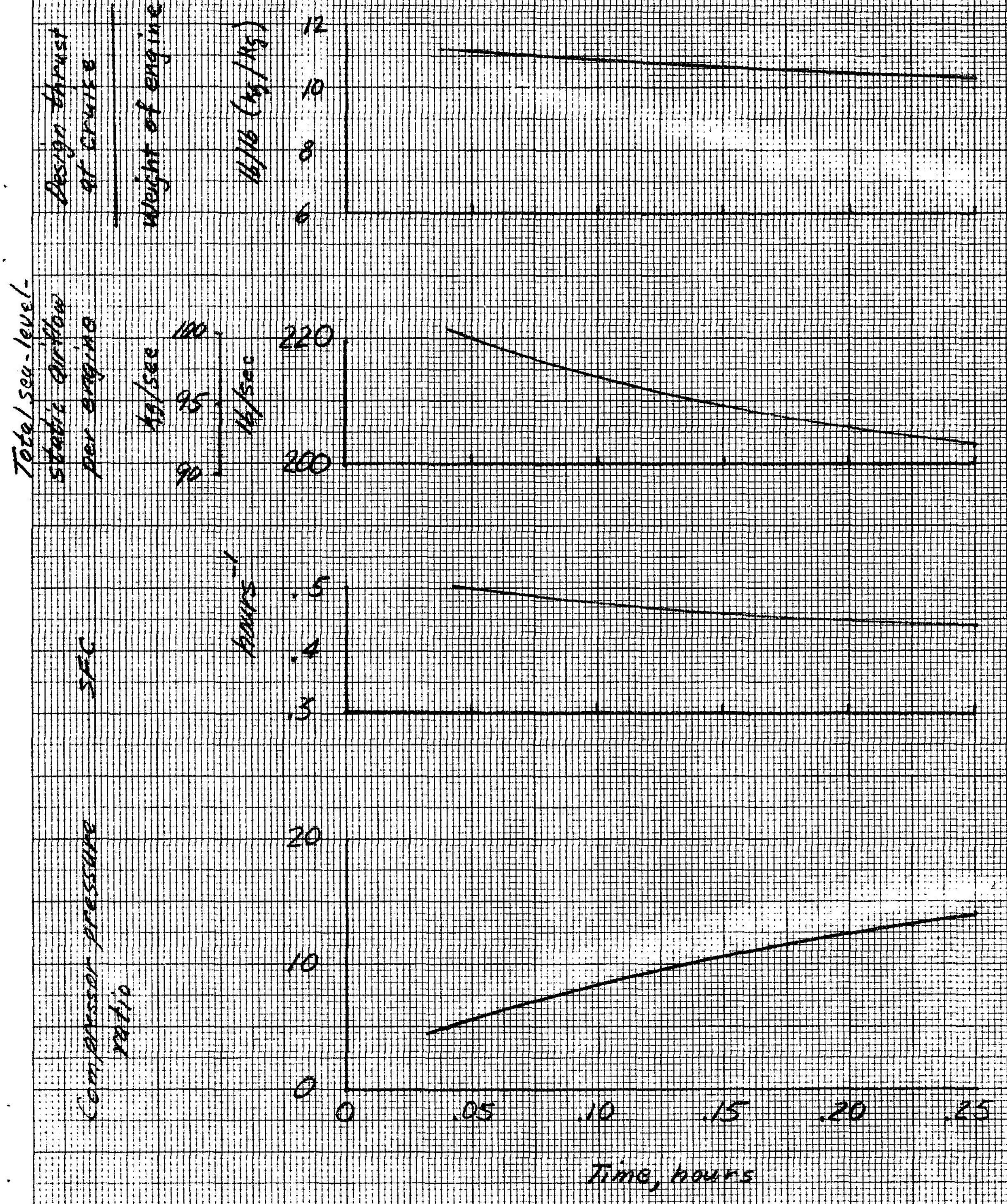

Figure 10.– Engine parameters for dry turbojets scaled to produce 20000 lb (9160 kg) net thrust at MN = 0.3, sea-level using H_2 fuel. Weight factor = 1.0, turbine-inlet temperature = 2500°F (1370°K)

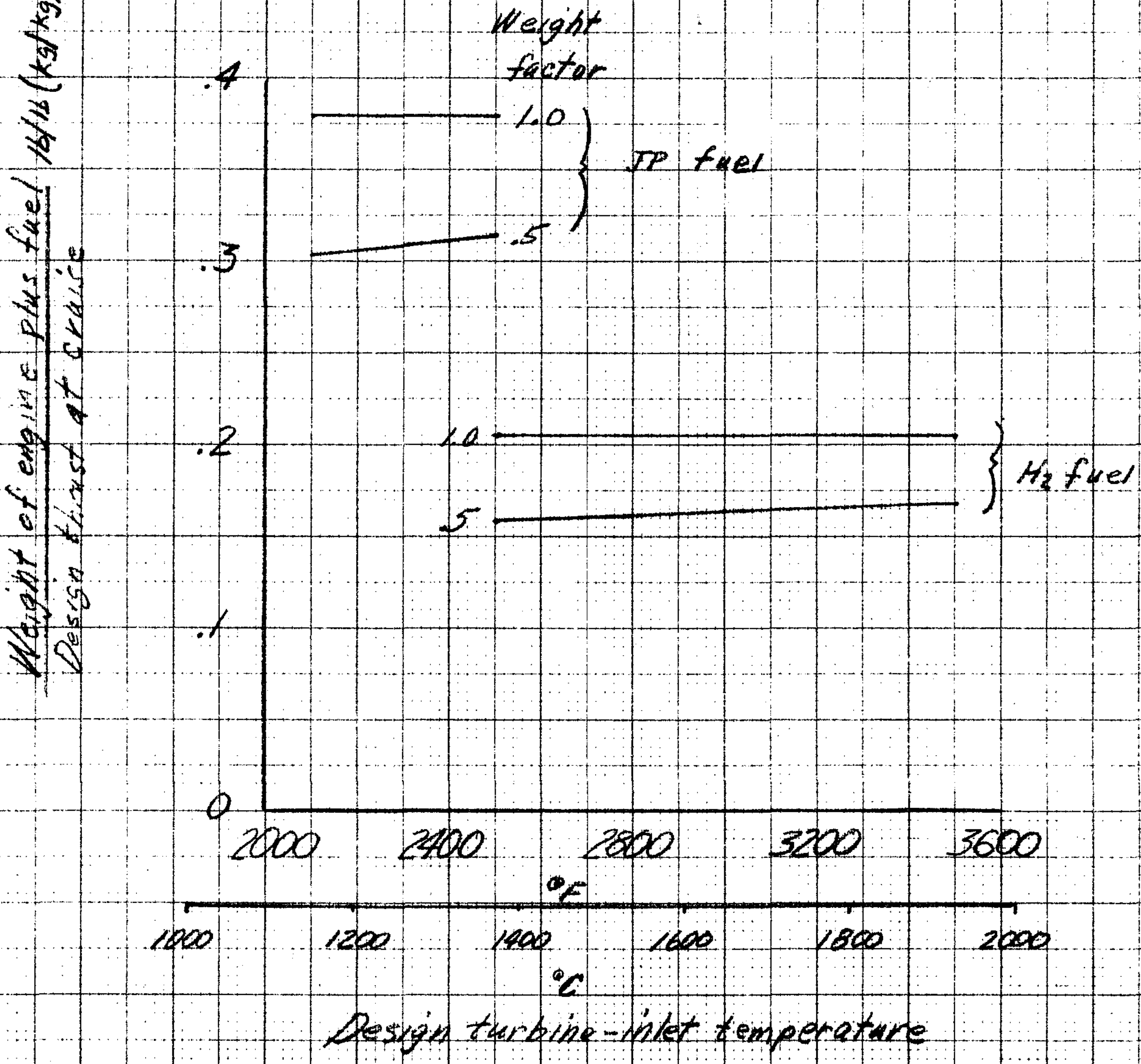

Figure 11. - Summary of optimized turbojet engines scaled to produce 20000 lb (9160 kg) net thrust at MN=0.3, sea-level. Cruise time - .25 hours.

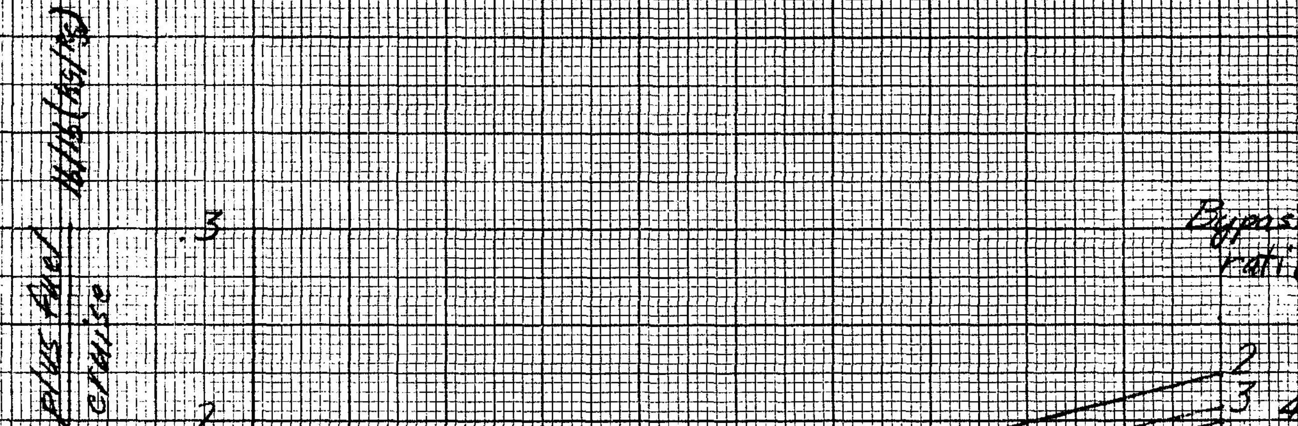

Figure 12. Optimum and fixed bypass ratio dry turbofan engines scaled to produce 20000 lb (9160 kg) net thrust at MN = 0.3, sea-level using H_2 fuel. Weight factor = 1.0. Turbine-inlet temperature = 2500°F (1370°C)

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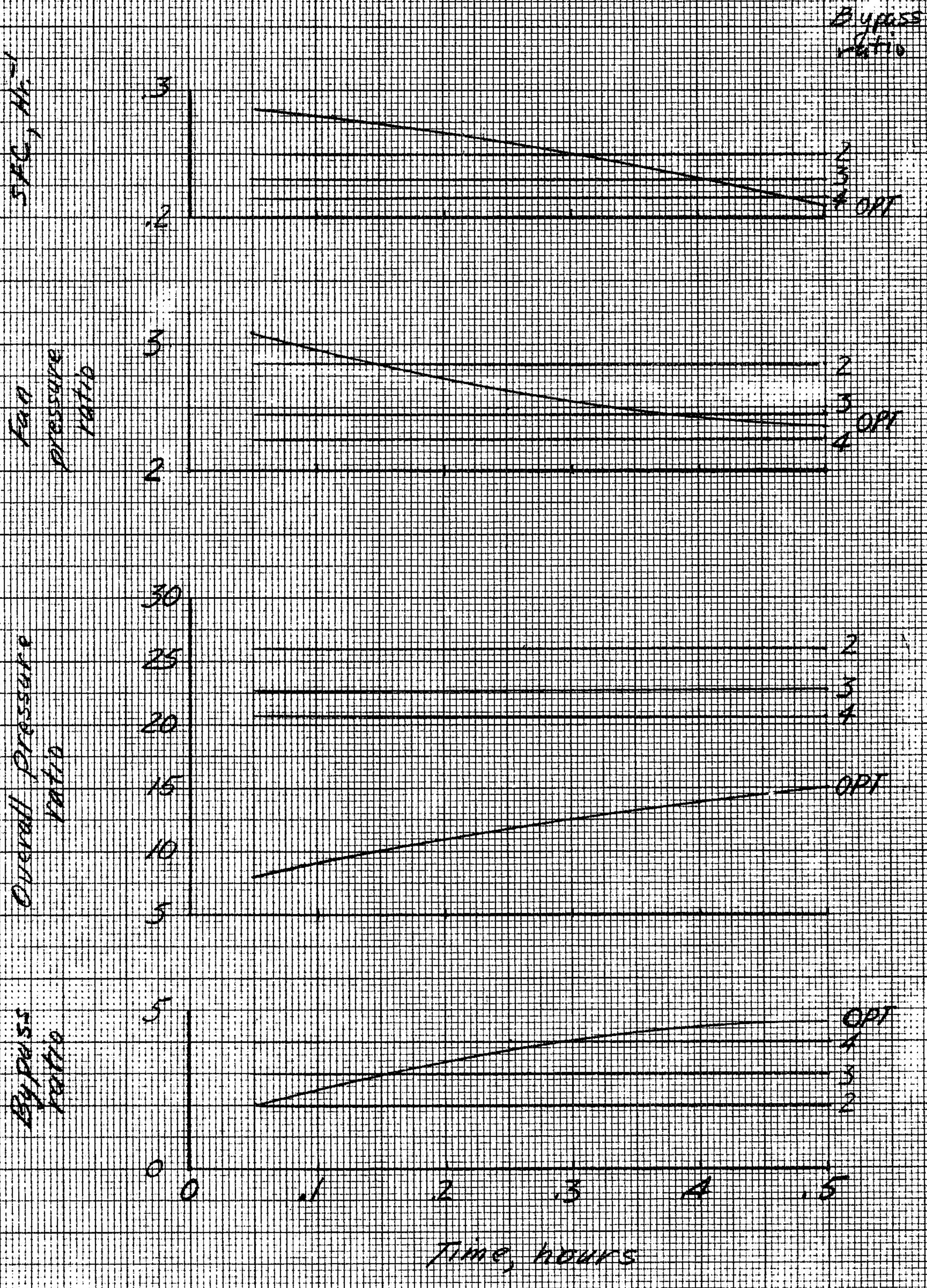

Figure 13.- Engine parameters for dry turbofan engines scaled to produce 20000 lb (9160 kg) net thrust at MN=0.3, sea-level using H_2 fuel. Weight factor = 1.0. Turbine-inlet temperature = 2500°F (1370°C)

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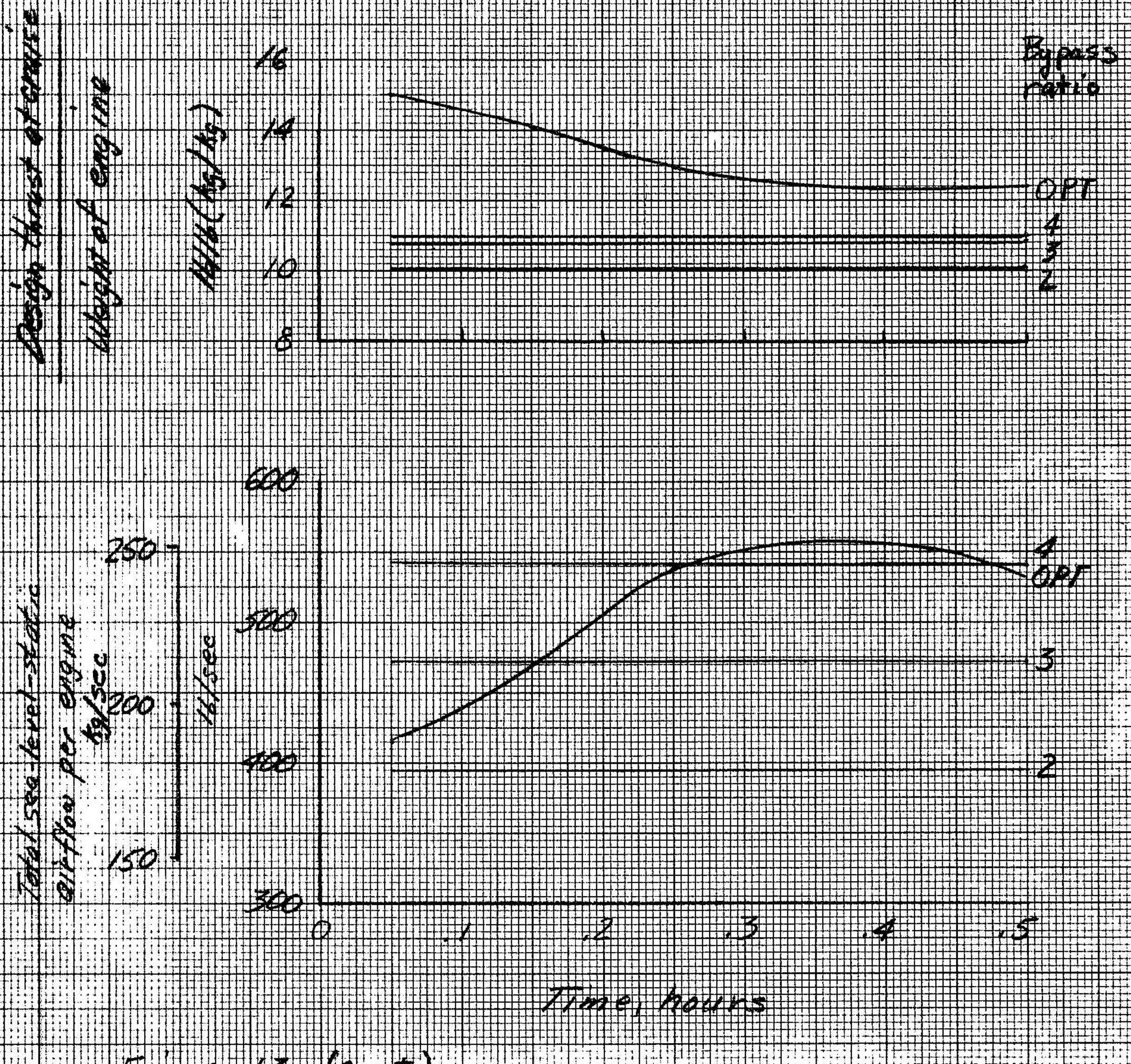

Figure 13.- (cont.)

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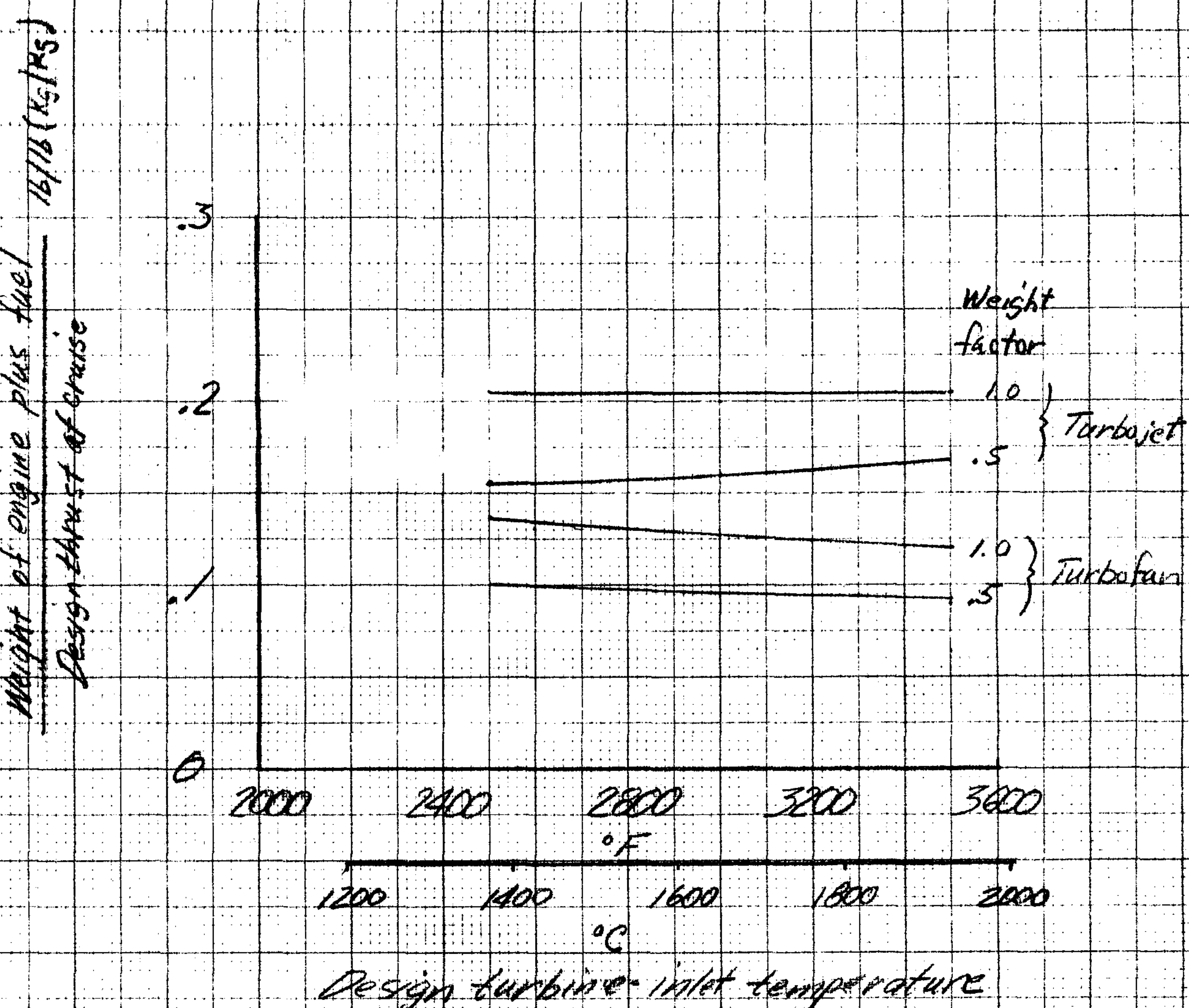

Figure 14. – Summary of optimized turbofans and turbojets scaled to produce 20000 lb (9160 kg) net thrust at MN = 0.3, sea-level. H_2 fuel. Cruise time = .25 hours.